

Diffractive Optics Fabricated by Direct Write Methods with an Electron Beam.

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1. Introduction.

State-of-the-art diffractive optics are fabricated using e-beam lithography and dry etching techniques to achieve multilevel phase elements with very high diffraction efficiencies. One of the major challenges encountered in fabricating diffractive optics is the small feature sizes required (e.g. for diffractive lenses with small f-number). It is not only the e-beam system which dictates the feature size limitations, but also the alignment systems (mask aligner) and the materials (e-beam and photo resists). In order to allow diffractive optics to be used in new optoelectronic systems, it is necessary not only to fabricate elements with small feature sizes but also to do so in an economical fashion. Since price of a multilevel diffractive optical element is closely related to the e-beam writing time and the number of etching steps, we need to decrease the writing time and etching steps without affecting the quality of the element. To do this one has to utilize the full potentials of the e-beam writing system.

In this paper, we will present 3 diffractive optics fabrication techniques which will reduce the number of process steps, the writing time and the overall fabrication time for multilevel phase diffractive optics.

2. Conventional fabrication technique.

Most multilevel phase surface relief structures are fabricated by utilizing n binary amplitude masks in n standard photolithography processes to achieve 2^n relief levels [1]. A standard photolithography process cycle for a single mask consists of the following steps (*Fig.1*):

- 1) Spin photo-resist on substrate
- 2) Place substrate in contact with chrome mask (or project mask pattern onto substrate), and illuminate with U-V radiation.
- 3) Process substrate to remove resist in exposed regions (for positive resist).
- 4) Place substrate in ion milling machine to create relief patterns.
- 5) Remove old resist.

Thus for a 16 phase level diffractive optics, 20 (=4x5) processing steps are required to complete the fabrication. Typically, this method allows fabrication of structures down to 1 micron (mainly limited by mask aligner type and the number of re-alignments required between masks). It is easy to see that this fabrication technique is very laborious and time consuming, and subject to many processing errors, which directly influence the cost of production. This is because this fabrication technique does not fully utilize the power and capabilities of the e-beam writing system.

3. Various improvements on the fabrication of multilevel relief structures using e-beam direct write techniques.

3.1) Direct write on e-beam resist.

In order to decrease the misregistrations between mask alignments, we have developed a fabrication technique which does not rely on amplitude masks. The different binary patterns are directly aligned and written on the e-beam resist on the substrate in the e-beam machine. Between each e-beam writing steps, a photolithographic and an etching step are involved (see *Fig.2*). Since the e-beam machine is capable of automatically locking onto etched alignment marks and aligning the next pattern with respect to these marks, the alignment misregistrations errors are decreased to 0.1 micron. This allows the user to fabricate multilevel relief structures with features down to 0.5 micron. However, even though the misregistrations errors and the feature sizes are decreased, this method still requires long fabrication time because the substrate needs to be recoated with chrome and entered in the e-beam n times (for 2^n relief levels).

3.2) Direct write on e-beam sensitive photoresist

In order to cut down the processing time, we used a photoresist which is sensitive to electron beams (Hoechst AZ-5214-E photoresist) in place of the e-beam resist. *Fig.3* shows a comparison of the number of photolithographic processes used by each method. Since the photo resist can be exposed by the e-beam writer and then directly used in the etching process, the photolithographic steps between e-beam writing and ion milling are eliminated.

3.3) Direct write with various e-beam spot sizes.

To reduce the e-beam writing time, we have utilized a variable e-beam spot size to write fringes or shapes of different sizes. Since many diffractive optics patterns are composed of e-beam shapes whose sizes vary considerably over the aperture, these patterns can be

written more efficiently in time by increasing the spot size to write coarser features, and decreasing it to write finer features.

Although the e-beam has to run n different patterns for n spot sizes, the writing time can be decreased considerably if the partitioning between large and finer features is made in an efficient way. *Fig. 4* shows a spherical on-axis zone plate whose shapes have been partitioned into two different files to be written with two different spot sizes. Here, the first spot size is of 0.1 micron and the second of 0.2 micron. The gain in writing time is about 35%. The maximum spot size is limited by the maximum beam current (the larger the spot size, the higher the current): for a spot size of 0.1 micron, the beam current has to be set at least to 8 nA while for a spot size of 0.4 micron the beam current is only of 100 nA. More complex patterns can be further partitioned into more sub-patterns to be written with spot sizes ranging from 0.025 to 0.8 micron. However, the amount of time required to set the exact e-beam current for the intended spot size manually by the e-beam operator when using more than two spot sizes has also to be considered.

3.4) Direct write with various e-beam dosages on analog e-beam resist.

In order to significantly decrease the fabrication steps and to enable the fabrication of features down to 0.1 micron, we used a direct write method where the e-beam exposure on an analog resist varies over the desired pattern. This method requires a single e-beam run and a single etching process (with no photolithographic step) to fabricate a multilevel phase CGH. In standard e-beam lithography, an e-beam exposure contains enough electron dose in the exposed regions of the e-beam resist to fully clear the resist during the development process (for a positive e-beam resist). If the electron dose and/or the development process is reduced, it is possible for the e-beam resist to not fully develop. This is possible since the solubility of the resist in the developer varies with the electron dose, i.e. the higher the dose, the faster the resist dissolves in the developer. This allows different thickness control of e-beam resist simply by varying the electron dose. *Fig.5* shows the large decrease in fabrication steps when using this technique. The misregistration errors are decreased to the e-beam misregistration in field addressing, which is typically of 0.025 micron. Thus the fabrication of features down to 0.1 micron is only limited by the resist development, and no more by the alignment accuracy.

Two types of e-beam substrates have been used; one for reflection mode and one for transmissive mode diffractive optics. For reflection mode, a standard chrome on glass e-beam plate was used. For transmissive mode, an e-beam plate with an optically transparent layer of ITO (indium-tin-oxide) was used in place of the chrome. Two positive analog e-beam resists have been successfully used: EBR-9 (Toray) and PMMA (KTI 950K 9%). Since EBR-9 could not be coated thicker than approximately 500nm, its use was limited to reflection mode diffractive optics. PMMA was used for thicker layers (up to 2 microns thick), and was successfully applied to transmissive mode diffractive optics. The amounts of EBR-9 and PMMA resist removed by the developer are shown in *Fig.6*.

4. Experimental results.

Several CGHs have been fabricated by using the different e-beam direct write methods described in this paper. Diffractive cylindrical and spherical lenses have been fabricated using the direct write on e-beam resist discussed in section 3.1 (see Fig.7). A set of linear gratings has been fabricated in analog e-beam sensitive photo resist as discussed in section 3.2, then etched successfully into glass (see Fig.8). A CGH for wavefront transformation is under fabrication using the various spot sizes method as discussed in section 3.3. Several arrays of CGHs have also been fabricated using the direct write on analog e-beam resist using 16 different e-beam dosages as discussed in section 3.4: Fig.9 shows a 128 by 128 lenslet array of $f/5$ lenses with 50 microns diameter. Fig.10 shows a diffractive lens out of the 2 by 2 array performing the space semi variant shuffle exchange optical interconnect. Fig.11 shows a CGH out of the 64 by 64 CGH array performing the hypercube interconnection architecture; each CGH has been calculated by the Gerchberg-Saxton iterative algorithm [2]. Two optical reconstructions are shown when only one CGH out of the 64 by 64 CGHs is illuminated.

5. Conclusion.

We presented several new e-beam microlithographic fabrication techniques for the fabrication of multilevel surface relief phase structures for diffractive optics. These fabrication techniques have several advantages over the conventional fabrication technique described in *ref.1*. For example, the direct write on e-beam resist decreases significantly the misalignment errors which occur usually during the pattern transfers in the mask aligner, and decreases the minimum feature sizes allowed for fabrication. The e-beam sensitive photoresist contribute to reduction in processing time during the photolithography process, and the variation of the e-beam spot size decreases the overall e-beam writing time by writing the fractured patterns in a more efficient way. E-beam direct write on analog e-beam resist with various e-beam dosages can generate a sixteen phase level element in one exposure step and one processing step.

Acknowledgments

We would like to thank Jiao Fan and Peng Li for their contributions in the holographic pattern fracture and the e-beam data file preparation.

References.

- [1] G.J.Swanson, *MIT technical Report 854*, 17-24 (1989).
- [2] R.W. Gerchberg and W.O.Saxton, *Optik 35*, 237-246 (1972).

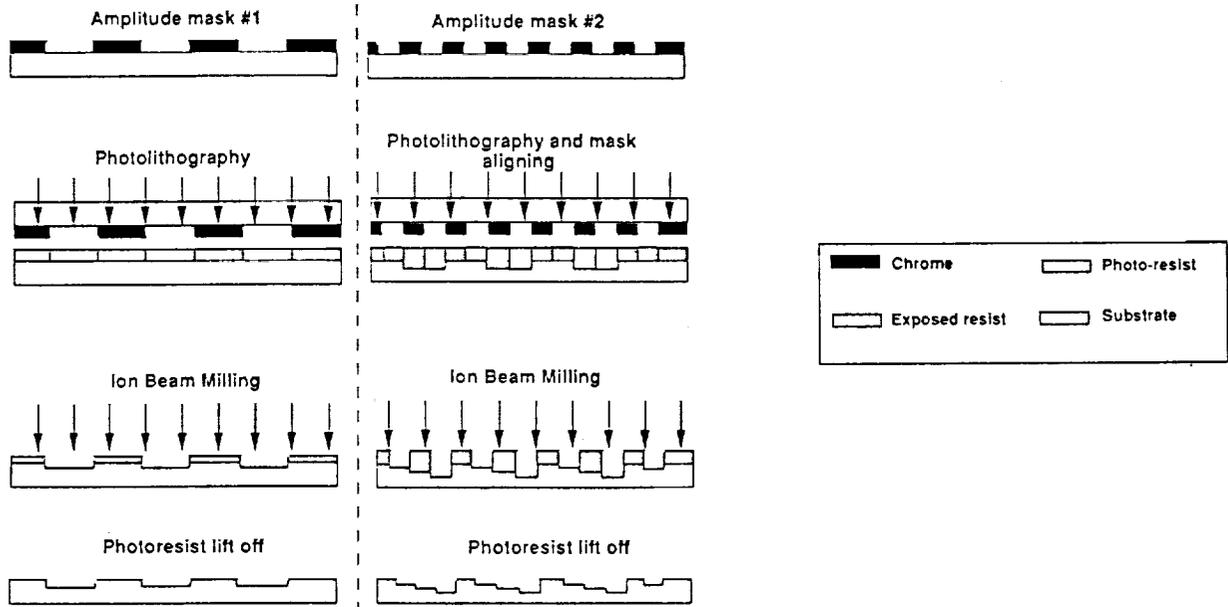


Fig.1) Conventional fabrication technique to produce multilevel relief phase structures.

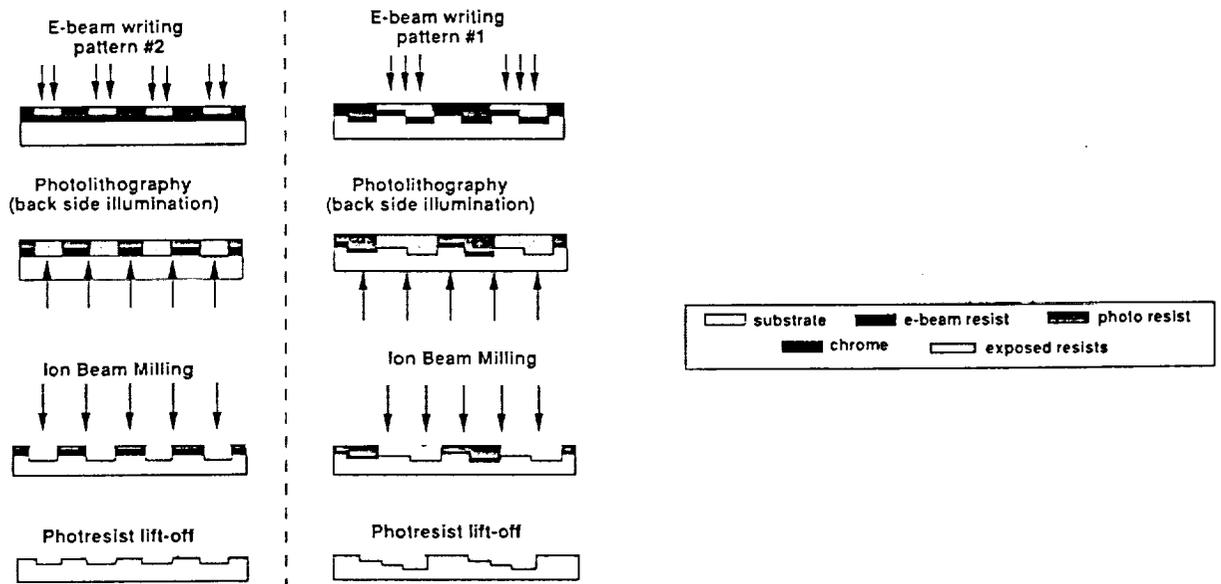


Fig.2) Direct write on e-beam resist, overcoming the need of using optical mask aligner. Pattern #2 is written first because it contains finer and shallower structures than pattern#1.

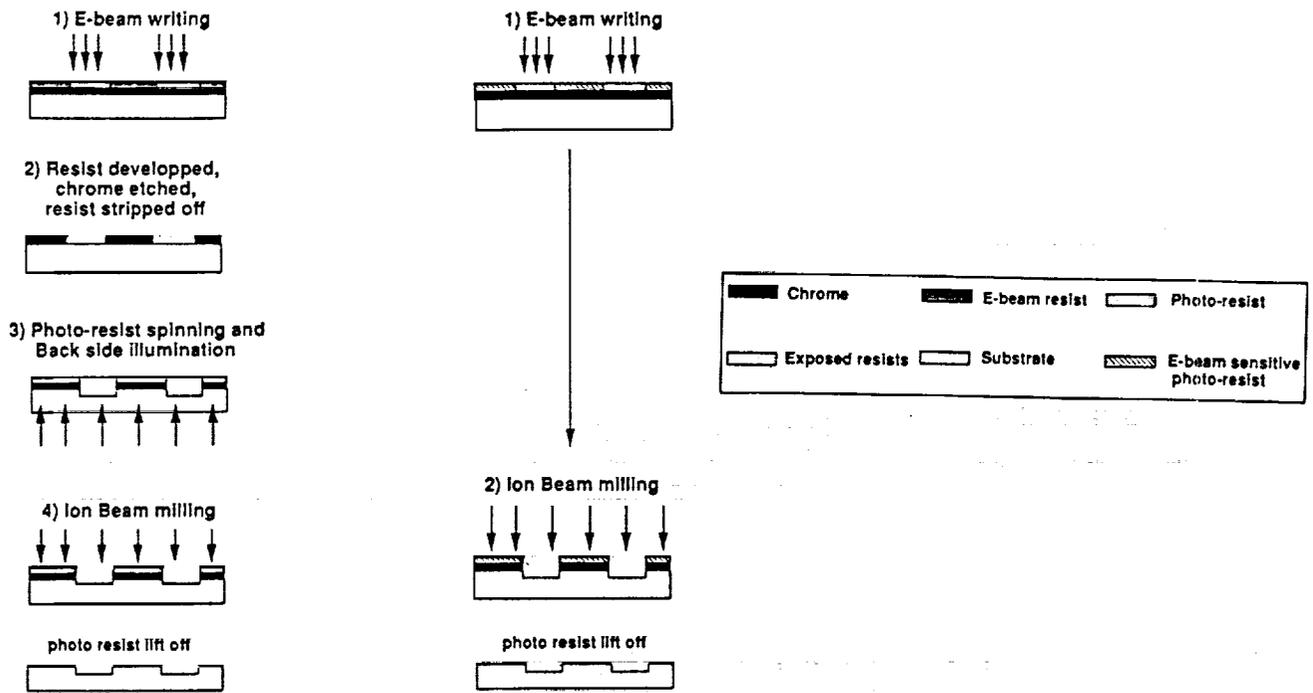
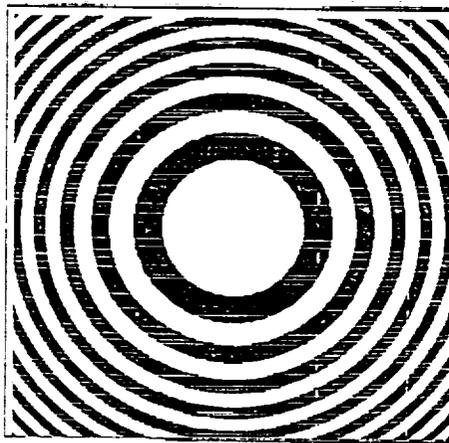
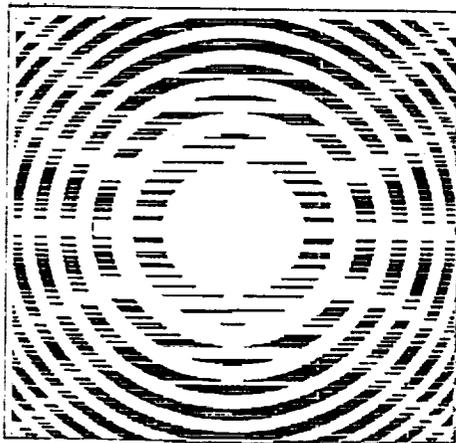


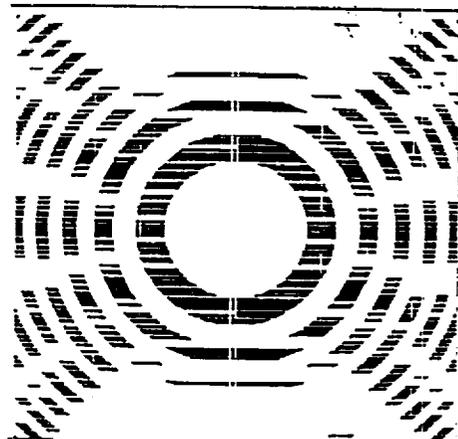
Fig.3) Comparison of processing steps (a) using regular e-beam resist, (b) using e-beam sensitive photoresist.



4.a) Original spherical lens ($f=1\text{mm}$, dimension= $150\text{ microns} \times 150\text{ microns}$).



4.b) Fine shapes written with 0.1 micron spot size.



4.c) Coarse shapes written with 0.2 micron spot size.

Fig.4) Direct write with various e-beam spot sizes.

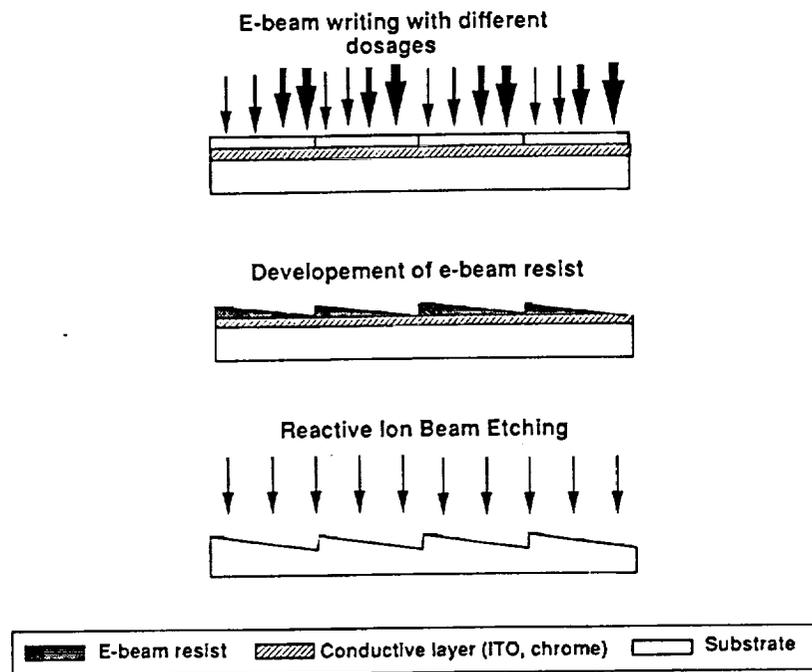


Fig.5) Direct write with various e-beam dosages on analog e-beam resist.

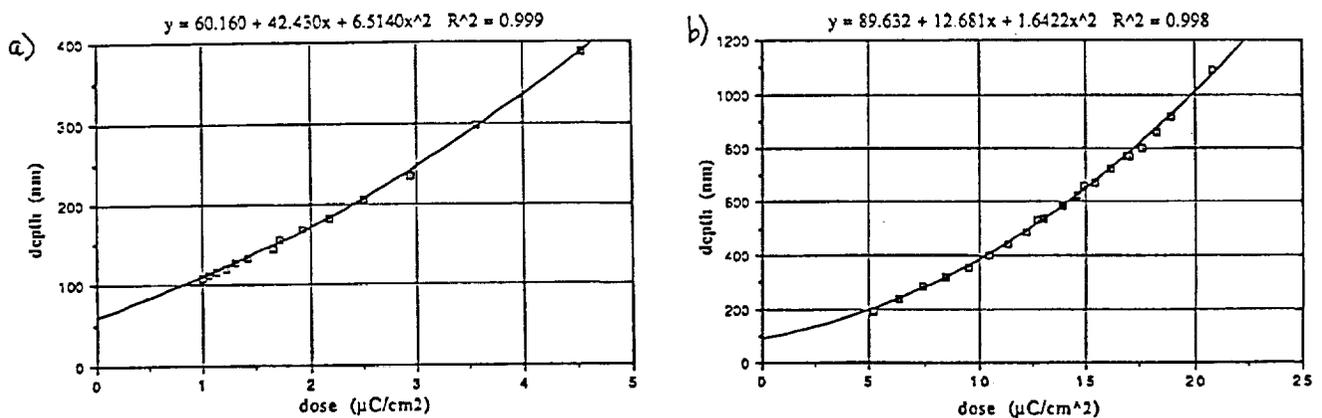


Fig.6) Depth vs. electron dose for a): EBR-9 Torray resist, and for b): PMMA resist. Equation shows second order polynomial fit (correlation coefficient R).

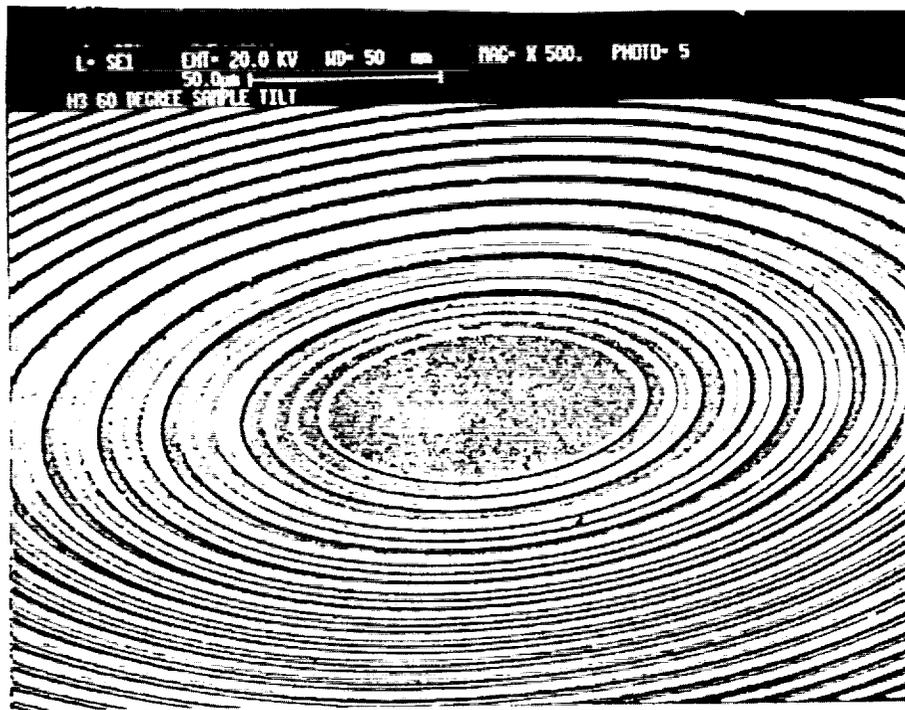


Fig.7) Four phase level f/1 diffractive lens fabricated by the direct write on e-beam resist, (method described in section 3.1).

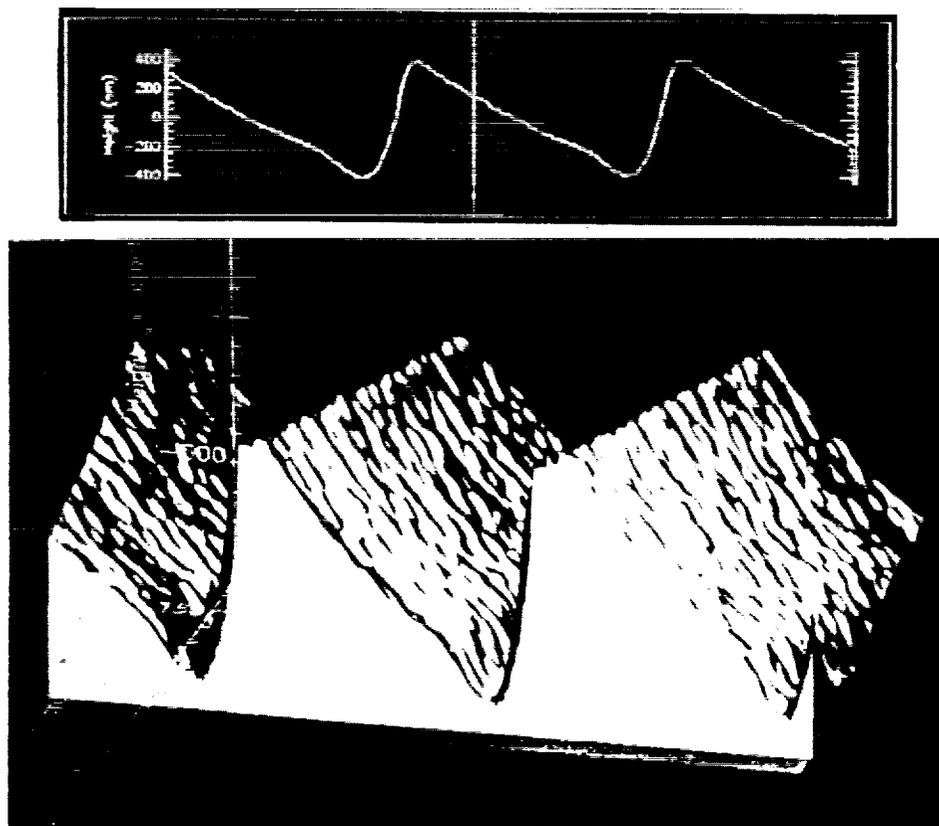


Fig.8) Linear grating of 60 microns period fabricated with the e-beam sensitive photoresist method (discussed in section 3.2) and etched into glass.

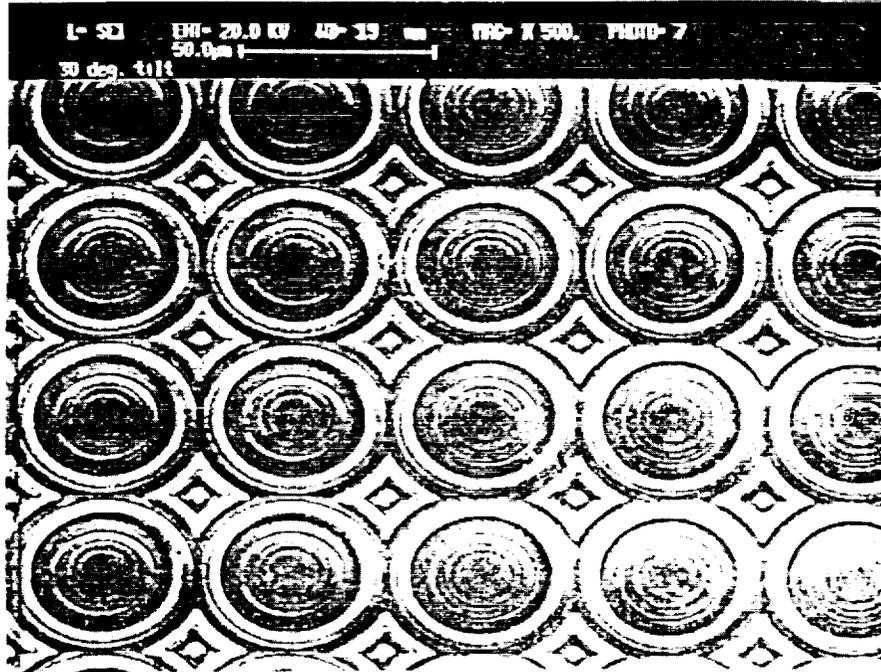


Fig.9) SEM microphotograph of a 128 by 128 lenslet array (f15, diameter: 50 microns) fabricated by direct write on analog e-beam resist using 16 different e-beam dosages.

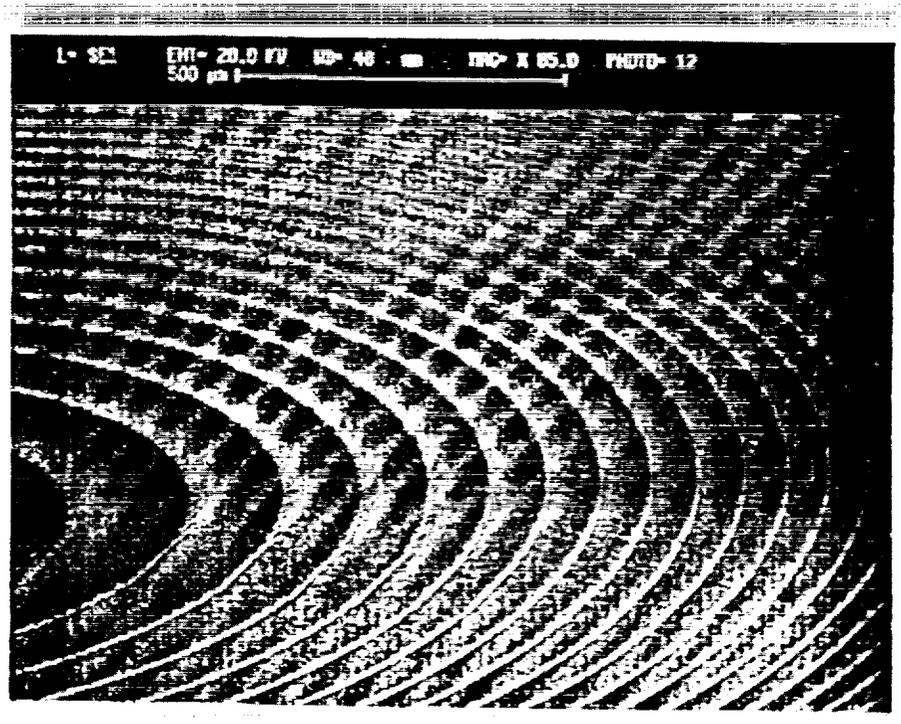
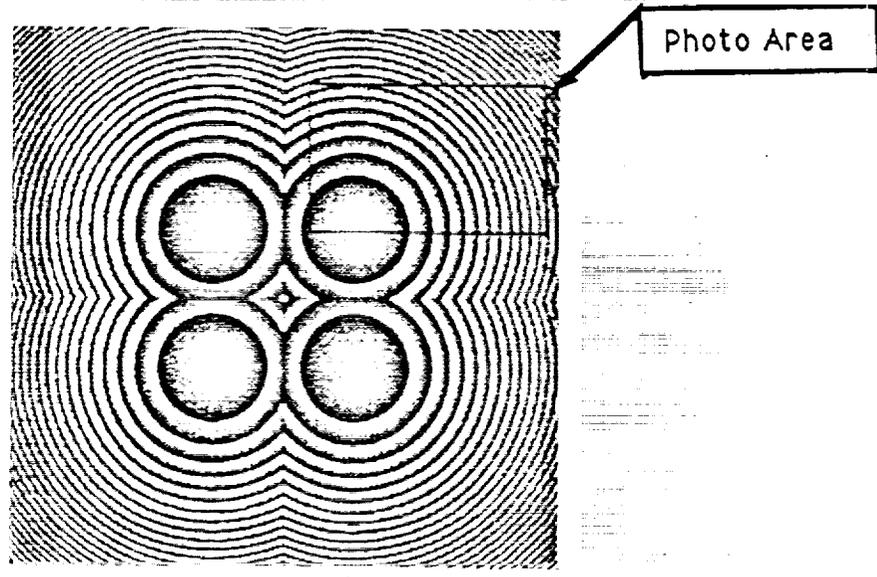


Fig.10) SEM microphotograph of a diffractive off-axis Fresnel zone plate out of a 2 by 2 space semi variant shuffle exchange interconnection architecture, fabricated by direct write on analog e-beam resist using 16 different e-beam dosages.

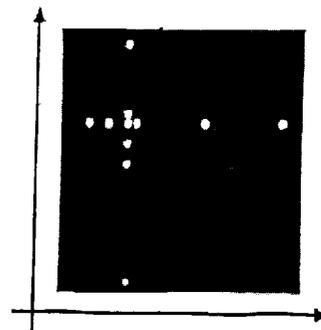
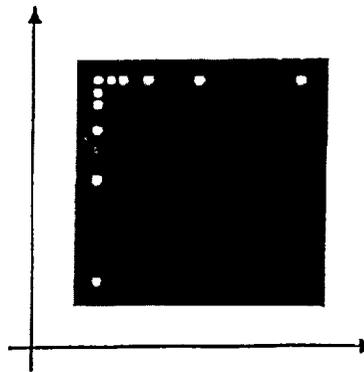
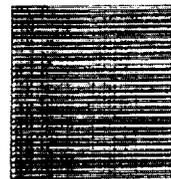
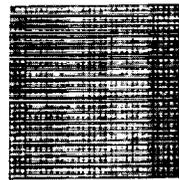
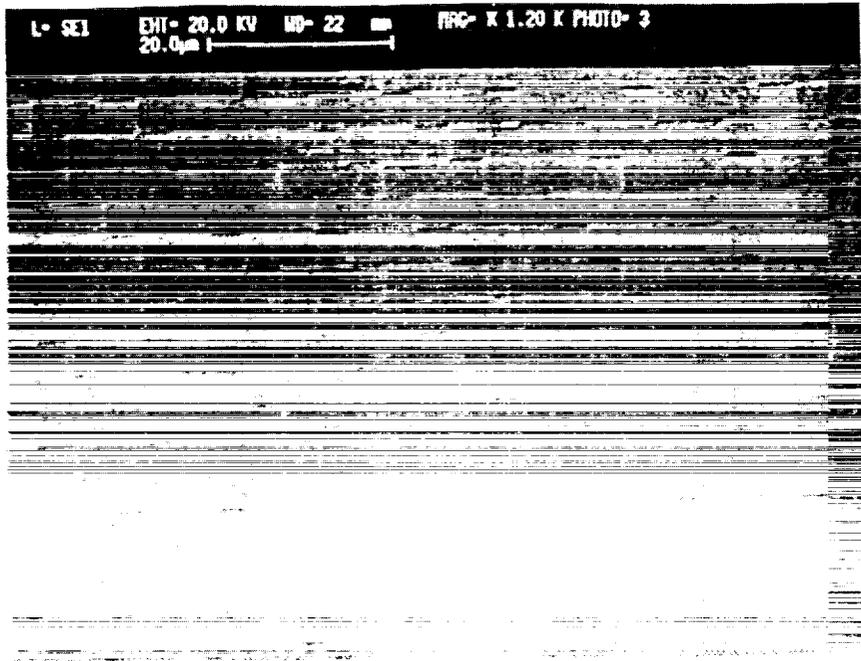


Fig.11) SEM microphotograph of a Fourier CGH out of a 64 by 64 array performing the hypercube interconnection architecture, fabricated by direct write on analog e-beam resist using 16 different e-beam dosages. The CGHs were calculated using the Gerchberg-Saxton iterative algorithm. Two optical reconstructions are shown when only one CGH out of the 64 by 64 array is illuminated.

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